

M31, M33 and the Milky Way: Similarities and Differences

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Abstract

The large galaxies in the Local Group, while all disk galaxies, have diverse stellar populations. A better understanding of these differences, and a physical understanding of the causes, requires more detailed study of the older populations. This presents a significant challenge to GAIA but the scientific returns are also significant.

1 INTRODUCTION

Study of the resolved stellar populations of galaxies in the Local Group offers great scientific returns in our understanding of how galaxies form and evolve. The Local Group member galaxies (cf. [1]) include the three disk galaxies M31, M33 and the Milky Way, and numerous dwarf companions, both gas-rich and gas poor. What causes their similarities and also their diversity?

There are two main aspects to galaxy formation and evolution, namely the history of *mass assembly and re-arrangement* and the history of *star formation*. The old stellar populations play a particular role in deciphering these histories, since old stars usually retain a memory of certain aspects of their early life, such as the surface chemical abundances, and often orbital angular momentum and orbital energy.

The important questions concerning the mass assembly, apart from its rate, both past and present-day, include: what was the nature of the mass? – since collisionless dark matter, collisionless stars and collisional gas behave differently; what was the density distribution of any and all components? – since physical processes such as tidal stripping depend on relative densities, and dynamical friction timescale depends on mass ratios; what are the specific angular momenta and orbits? – since the coupling efficiencies of various processes depend on these.

The important questions concerning star formation history include: what was the rate of star formation and how did/does it vary as function of spatial location?; what was and is the stellar Initial Mass Function? – the visibility of galaxies at high redshift, their contributions to background light in different passbands, their chemical enrichment, stellar feedback, the supernova rate, gas consumption rate etc. depend on the IMF; what was/is the mode of star formation? – what fraction formed in super star clusters?; and of course – what is the connection to the history of mass assembly of the various components.

Spiral galaxies are clearly diverse in their properties, for example in bulge-to-disk ratio, but theories should be able to produce the galaxy population in the Local Group rather naturally, without appeal to special conditions. Thus the Local Group members are ‘typical’ galaxies in

their properties and for theory, but they are atypical for observation. From their resolved stellar populations we can obtain age distributions, chemical elemental abundance distributions, kinematics – all as a function of spatial location. The tracers that can be used include stars of a range of evolutionary stage and mass, planetary nebulae, star clusters, and gas through HII regions, 21cm emission and CO emission. The stellar properties in satellite companion galaxies provide important complementary constraints, for example, limiting the possible contribution of disrupted satellites to larger systems (cf. [2]).

We have learned much about the Milky Way Galaxy from its resolved stellar populations, but we still have only an incomplete picture, and it is clear that GAIA will play a major role in furthering our understanding. Study of M31 and M33 with existing ground-based telescopes and with the Hubble Space Telescope has been limited, but as I will describe below, has provided clear evidence of differences in some aspects of their stellar populations and also of similarities.

While detailed space motions and distances have a unique role to play in understanding how the Local Group disk galaxies decompose into different stellar components such as bulge/halo/disk/thick disk, much can be inferred from mean kinematic quantities, such as the net azimuthal streaming motion of a population. To illustrate, Figure 1 shows the specific angular momentum distributions for these components of the Milky Way. The similarity between the angular momentum curves for the bulge and stellar halo can be explained by a model in which the proto-bulge gas is ejected from star forming regions in the early halo [3], while the similarity between the curves for the thick and thin disks is expected in a model where the thick disk is a remnant of the early stages of disk formation (see below). It is clear that ejecta from the halo did not ‘pre-enrich’ the disk.

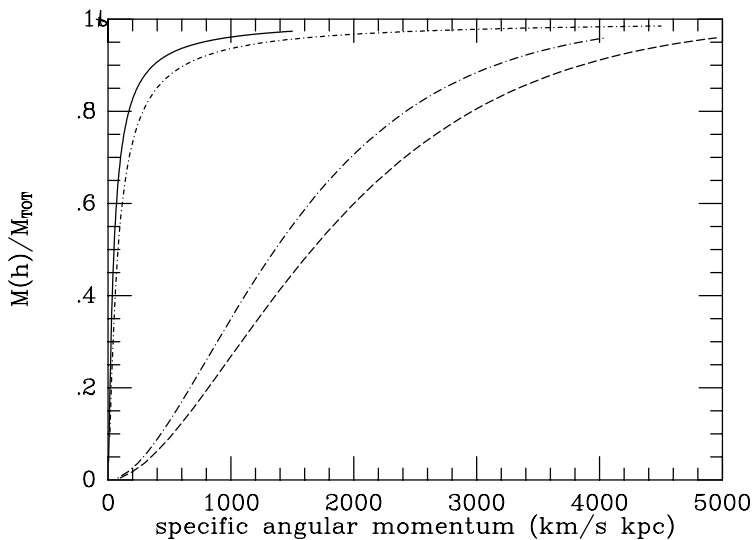


Fig. 1. Estimated angular momentum distributions for the stellar components of the Milky Way. The curves correspond to, from the left, the central bulge, the stellar halo, the thick disk and the thin disk. This figure is taken from Wyse & Gilmore [3].

Old stars are important for deciphering both the mass assembly and star formation histories, and this poses a significant challenge for GAIA capabilities, since at a distance modulus of

~ 24.5 , the tip of the Red Giant Branch (T-RGB) in M31 is at $I \sim 20.5$ [4], and there is no good evidence for an intermediate-age population in the bulge of M31 that would contribute Asymptotic Giant Branch (AGB) stars brighter than the tip [5]. However, significant scientific returns would be achievable with mean kinematics of red giants in M31, M33 and their satellites, as I describe below. I hope to convey the exciting science that could be possible were GAIA to push through its nominal limit of $G = 20$ ($I \sim 20$), to reach below the T-RGB. Of course, for those galaxies with (intermediate-age) stars brighter than the old T-RGB, the nominal GAIA limit will still provide significant results.

I will first describe some of the advances we have made so far through study of the stellar populations of the Milky Way. I will then discuss what is known of the stellar populations of the remaining large members of the Local Group, and raise some open questions, including ones that may be addressed with GAIA.

2 THE THICK DISK AND CONSTRAINTS ON MASS ASSEMBLY OF THE MILKY WAY GALAXY

The effects of mergers between galaxies are to fatten disks, by putting orbital energy of the galaxies into their internal degrees of freedom, and to build up bulges and haloes, through a combination of heating and angular momentum and mass re-arrangement resulting from gravitational torques and bar formation, and assimilation of stars removed from their parent galaxy by tidal effects. The amplitudes of these effects are dependent on the (many) parameters of the interaction, such as mass ratio of the merging systems, gas content, orbital inclination and angular momentum (both the sense and the magnitude). The age distributions, kinematics and metallicities of the different stellar components of a galaxy – and of different tracers, such as young stars, old stars, or globular clusters – are very important in deciphering a complex situation, in which some properties can be approximately conserved (such as angular momentum of a stellar orbit or stellar metallicity) and some are not (such as the velocity dispersions of the disk stellar population).

A merger between a stellar disk and a stellar satellite of around 10-20% by mass results in a fattening of the disk (as opposed to the destruction of the disk that happens for mass ratios that are more equal), and the thinness of disks can be used to constrain their merging history (cf. [6]) and cosmological parameters [7]. Indeed recent N-body simulations [8,9] have produced fattened disks that have spatial distributions and kinematics rather similar to the thick disk of the Milky Way Galaxy (see [10] for a recent review). This is particularly interesting for the mass assembly history, since the thick disk, at least at the solar circle, is exclusively *old*, as illustrated in Figure 2. We know that the thin disk has been forming stars fairly continuously over the last ~ 12 Gyr [15], with the consequence that if a significant merger had occurred more recently, younger stars would also be in a thicker disk. However, these younger stars are not observed in the thick disk (cf. [16–19]). Thus the last significant merger of the Milky Way occurred ~ 12 Gyr ago, when the globular clusters like 47 Tuc were formed. Of course, if the thick disk is not the product of a ‘minor’ merger, but e.g. formed by slow settling of the proto-disk to the disk plane [20] then the merging history is even more quiescent!

Further, the thick disk contributes $\gtrsim 10\%$ of stars in the solar neighbourhood, and falls off perpendicular to the plane with a scale-height 3–4 times that of the thin disk. Thus a significant fraction, some $\sim 30\%$, of disk stars at the solar Galactocentric distance, 2–3 scale-lengths from the centre, formed at lookback times of ~ 12 Gyr, or at redshifts ~ 2 . This is not easily understood in the context of hierarchical-clustering models of structure formation, such as the cold-dark-matter scenario. In these models, the angular momentum transport that accompanies the merging process to form galaxies [21,22] leads to disks that are too small, and

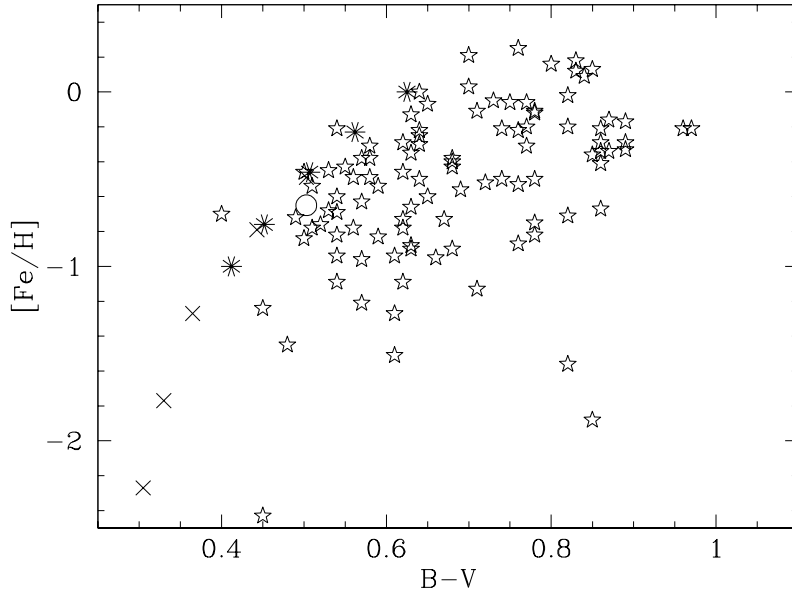


Fig. 2. Scatter plot of iron abundance *vs* B–V colour for thick disk F/G stars, selected *in situ* in the South Galactic Pole at 1-2kpc above the Galactic Plane (stars), together with the 14 Gyr turnoff colours (crosses) from VandenBerg & Bell [11] ($Y=0.2$) and 15 Gyr turnoff colours (asterisks) from VandenBerg [12] ($Y=0.25$). The open circle represents the turnoff colour (de-reddened) and metallicity of 47 Tuc (Hesser et al. [13]). The vast majority of thick disk stars lie to the red of these turnoff points, indicating that few, if any, stars in this population are younger than this globular cluster. This figure is based on Fig. 6 of Gilmore, Wyse & Jones [14].

one must appeal to ‘feedback’ processes to delay disk formation, to redshifts \lesssim unity [23,24]. This is perhaps another way of saying that the merging history of the Milky Way appears to be unusual in these models. But is the Milky Way unusual? What of the other large galaxies in the Local Group? There are clearly some large, relaxed-looking disk galaxies at redshifts of unity [25] – can we identify their counterparts and descendants locally?

First, we need to establish the properties of the thick disk in the Milky Way far from the solar Galactocentric radius; GAIA will play a key role in this, providing accurate distances, metallicities, proper motions and radial velocities for tracer stars (main sequence turn-off stars, red giants, Horizontal Branch etc.) at distances as far as $\lesssim 20$ kpc.

3 THE THICK DISK, BULGE OR HALO OF M31

The globular clusters in the Milky Way have a bimodal metallicity distribution, with peaks at $[Fe/H] \sim -1.5$ dex and ~ -0.6 dex [26], and around one-third being in the metal-rich population. The clusters in these two peaks are further distinguished by kinematics and spatial distribution. The metal-poor population consists of the classic halo globular clusters, which are old and on orbits of low angular momentum. The metallicity and kinematics characteristic of the metal-rich globular clusters (of which 47 Tuc is a member) are very similar to those of the thick disk, and these clusters are usually ascribed to this population [26,27], though their concentration towards the centre of the Galaxy has led to their association with the

bulge [28, 29]. If indeed the last significant merger event experienced by the Milky Way formed the thick disk, one might expect there to be globular clusters associated with it, by analogy with the young ‘globular clusters’ (super star clusters) identified in merging systems [30]. Further, this merger could have initiated bulge formation, consistent with the similar characteristic ages of thick disk and bulge.

The globular clusters of M31 also have a bimodal metallicity distribution [31], with peaks at metallicities remarkably similar to those of the Milky Way system, and again most clusters being in the metal-poor population. Furthermore these two populations appear to be similarly distinct in their kinematics and spatial distributions, as are the two Milky Way globular cluster populations. The globular cluster systems of the Milky Way and M31 appear to be analogues of each other. Associating the more metal-rich globulars, with peak $[\text{Fe}/\text{H}] \sim -0.6$, with the thick disk, as in the Milky Way, would lead to the expectation of a field thick disk with similar mean metallicity.

The field stellar population of M31 has been studied through colour-magnitude diagrams (both ground-based and from the Hubble Space Telescope) of its evolved stars and spectroscopy of bright red giant branch stars. All studies [4, 32–36], following the pioneering work of Mould & Kristian [37], find that the dominant field population probed down the minor axis has a mean metallicity¹ of around ~ -0.6 dex, from projected distances of ~ 5 kpc out to ~ 20 kpc (the ‘bulge’ minor-axis effective radius is ~ 1.5 kpc [38], significantly larger than that of the Milky way). The metallicity distribution is asymmetric, and can be fit by the superposition of two populations, metal-poor and metal-rich, with peaks similar to the globular clusters, at ~ -1.5 dex and ~ -0.6 dex. The bulk of the stars, even out at 20 kpc, is in the metal-rich population. Thus unlike the case for the globular clusters, the field stars of the ‘halo’ in M31 are predominantly metal-rich. It should be remembered that these field stars are members of Baade’s ‘Population II’ [39, 40], raising the issues of which stars in the Milky Way should have been identified as ‘Pop II’ – perhaps [41] the members of the Milky Way thick disk, whose mean metallicity is comparable to that of the dominant population in M31’s ‘halo’. Indeed, perhaps the ‘halo’ in M31, which is rather flattened with an axial ratio of ~ 0.6 , is actually a thick disk (cf. [41]). This could have been formed during a significant merger – as discussed more fully in Ibata’s contribution, wide-area star counts of the evolved population in the ‘halo’ of M31 have revealed a large overdensity most easily explained as a remnant star stream from tidal interactions, albeit of the same high mean metallicity. Mean kinematics, as could be possible with GAIA, would provide further signatures of ‘streams’.

The red giant luminosity function, in fields at projected distances from the centre of ~ 1 kpc to ~ 20 kpc [4, 42], is consistent with no young, luminous AGB stars, providing a weak limit on the age distribution of the bulge/halo/thick disk of M31, as older than a few Gyr. The red giant luminosity functions are in fact very similar to that of the evolved stars in the Milky Way bulge (measured in Baade’s window, 4° from the centre), for which we know from deep photometry below the turnoff that the population is old [43]. Optical imaging of fields at projected distances from the centre of ~ 1 kpc also show no evidence for stars brighter than the tip of the RGB (after taking careful account of blending; [5, 44]).

The presence of RR Lyrae stars in the bulge/halo of M31 [45] argues for an old component, age $\gtrsim 10$ Gyr. Horizontal branch morphology can provide clues, though is not yet available; ground-based data thus far have prohibitively large errors by the $V \gtrsim 25$ level of the HB. HST studies of M31 up to now have been primarily globular cluster fields, mostly in fields with too much disk contamination to study the field halo/bulge.

¹Most of these metallicities are based on the colour of the red giant branch and are subject to calibration uncertainties including the elemental abundance mix.

Even more intriguing is the fact that colour-magnitude diagrams for fields in lines-of-sight that should be predominantly outer disk have a RGB morphology very similar to that of ‘halo’-dominated fields [46], with an additional metal-rich component that may be ‘thick disk’ [47] or simply the thin disk. There is apparently a significant old component in these outer disk fields, with important implications for the onset of disk formation [46], as indicated above. Or is the disk so warped that one cannot calculate reliably its contribution in a given line-of-sight, based on simple surface brightness profiles?

Thus the CMDs of M31 offer fascinating clues to the past history of our nearest large galaxy, but kinematics and metallicities are required to untangle the different populations projected into the same line-of-sight. Radial velocities of the bright giants are possible with 10-m class telescopes [34]. Multi-band wide-field mapping of the field population below the tip of the RGB i.e. $I \gtrsim 20.5$ is feasible with existing ground-based telescopes; GAIA could provide the information necessary for their interpretation through measurements of mean/systematic motions of populations defined by, for example, colour or position (as a reminder, at the distance of M31, ~ 750 kpc, expected individual proper motions are less than $\sim 100 \mu\text{arcsec/yr}$, somewhat less than the expected accuracy of GAIA measurements for stars with $G = 20$). The surface brightness at the effective radius of the ‘halo’ of M31 is $\mu_B \sim 22$ mag/sq arcsec [38], and determining the limiting background stellar surface brightness at which GAIA will achieve its full accuracy is obviously important. Out at 20kpc along the minor axis, where the bulge field is still metal-rich, the surface brightness is only $\mu_V \sim 30$ mag/sq. arcsec [48].

Even old, metal-rich stellar populations can contain small numbers of stars brighter than the T-RGB, as evidenced by the handful of Long Period Variables in the globular cluster 47 Tuc [49]. These are plausibly in the Thermally-Pulsing (TP) phase of the AGB [50] and their increased luminosity relative to metal-poor stellar populations may be related to mass loss at the Helium shell flash that marks the onset of the TP-AGB. Further, non-variable bright AGB stars are expected as the descendents of any ‘Blue Stragglers’ that may have formed, either in the field itself or perhaps in globular clusters that were later disrupted. Identification of these rare stars, possible through the full coverage across the face of the galaxy with GAIA, would be exciting.

4 M33 – HALO/BULGE AND CLUSTERS

The early work of Mould & Kristian [37] established that the field stars of M33 some ~ 7 kpc projected distance from the centre of that galaxy, along the minor axis and thus expected to have little contribution from the disk, have a mean metallicity of only ~ -2 dex, with a small spread. There is a kinematic ‘halo’ as traced by the globular clusters [51]. Analysis of the CMDs resulting from deep imaging with the Hubble Space telescope [52] has shown that some of these ‘halo’ clusters have a red horizontal branch despite low metallicity (~ -1.5 dex), perhaps indicating a younger age (~ 7 Gyr), with others probably as old as the classical Galactic halo globular clusters. The field surrounding the globular clusters studied with HST are disk-dominated and show a complex star formation history [52].

Luminous star clusters have been identified across the face of M33 from HST images [53,54], with ages (inferred from integrated colours) ranging from $\lesssim 10^7$ yr to the $\sim 10^{10}$ yr of classical halo globular clusters. Derived masses are in the range of $10^2 M_\odot$ to $10^6 M_\odot$ and correlate with age, but there are apparently clusters of masses greater than $\sim 10^4 M_\odot$ with ages of only a few hundred million years [54]. There are some similarities to the populous intermediate-age clusters in the Large Magellanic Cloud [55] – is there some aspect of the star formation process in very late-type disk galaxies that favours populous clusters? The luminous stars in these clusters should be easily accessible to GAIA, allowing the association of the parent clusters

with disk, thick disk, bulge or halo.

Ground-based near-IR (J,K) imaging with adaptive optics on the CFHT, of the central regions of M33 (inner $18''$, or ~ 50 pc) find the fascinating result [56] that there is a strong AGB component, indicative of a burst of star formation 1–3 Gyr ago, but with metallicity only $\lesssim -1$ dex, much lower than the metallicity of the inner disk inferred from HII regions, of around the solar value (e.g. [57]). Why is the M33 inner bulge so different from that of M31 or of the Milky Way? How far out does the AGB component extend? Kinematics of the AGB population, and a larger-scale survey, are of obvious importance to attempt to understand the connections between disk and ‘bulge’, and the metal-poor ‘halo’. These stars are brighter than the Tip-RGB (by some 2.5 mag in the K-band, less so in the V-band) and should be amenable for study with GAIA.

5 M32 – AN ELLIPTICAL SINCE WHEN?

While not strictly part of my remit, the compact dwarf elliptical galaxy M32 offers an intriguing target for GAIA. The evolution of this galaxy has clearly been strongly influenced by its proximity to M31, and indeed a very plausible scenario invokes severe tidal truncation [58] perhaps of a former disk galaxy, to leave the central bulge [59]. There is a ubiquitous bright AGB population in M32, well-mixed with the underlying older stars [60]. Integral-field spectroscopy of the inner regions suggests that the typical population has around solar metallicity and an age of ~ 4 Gyr [61]. It has been speculated that the bright AGB stars are the remnant of a merger of some smaller system with M32 itself [60], or the result of gas inflow, star formation and mixing during the stripping of a disk galaxy [59]. These bright stars are ~ 3 mag brighter than the TRGB in the K-band, and again their mean kinematics should be measurable. This information, especially if the lower luminosity (older) stars are also accessible by pushing GAIA to its limits, should allow us to distinguish these two possibilities.

The proper motion of the centre-of-mass of M32, which should be measurable with GAIA, is obviously very important for deciphering the orbit and the past history of the interaction between M31 and M32.

6 SUMMARY

Cosmic variance requires that we confront theories of galaxy formation and evolution with the detailed properties of as diverse a sample of galaxies as possible. The Local Group offers the opportunity to study large galaxies with similar large-scale morphologies but different present-day stellar populations. GAIA could provide kinematic, distance and metallicity information to aid the deciphering of the histories of these different galaxies and thus the physics of galaxy evolution.

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